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A FILM COOLING EXPERIMENT ON A CONVERGENT-DIVERGENT NOZZLE

Henry F. Lewis and Dennis D. Horn
ARO, Inc.

June 1966

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FOREWORD

The research effort reported herein was sponsored by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC) under Program Element 62410034, Project 7778, Task 777805.

The research study presented was conducted by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contractor operator of AEDC, AFSC, Arnold Air Force Station, Tennessee, under Contract AF 40(600)-1200. The research was performed under ARO Project No. PL2289, and the manuscript was submitted for publication on March 22, 1966.

The authors gratefully acknowledge the assistance of Dr. Hall C. Roland of the University of Tennessee, under whose direction the theoretical nozzle adiabatic wall temperature distributions were calculated.

This technical report has been reviewed and is approved.

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ABSTRACT

A stainless steel, supersonic nozzle with an 11/16-in. -diam throat was successfully cooled using only a tangential air film. Mass fractions of cooling air film ranged from 0.190 to 0.302, and the maximum recorded wall temperature was 1800°F. Stilling chamber pressures ranged from 482 to 577 psia and temperatures from 2615 to 3460°F. Measured wall temperatures showed only limited agreement with a newly developed theory, with the theory underestimating adiabatic wall temperatures by from 20 to 30 percent.

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NOMENCLATURE

D	Nozzle diameter, in.
\dot{m}_c	Film air mass flow, lb _m /sec
\dot{m}_N	Nozzle mass flow (excluding film air), lb _m /sec
p _o	Total pressure, psia
S	Distance along nozzle wall from injection station, in.
T _c	Temperature of the injected air film, °F
T _o	Total temperature, °F
T _w	Nozzle wall temperature, °F
x	Nozzle axial coordinate, in.
y	Nozzle radial coordinate, in.
θ	Film air mass fraction, \dot{m}_c/\dot{m}_N

SECTION I INTRODUCTION

One of several problems inherent in the development of high enthalpy wind tunnels is the cooling of the throat of the expansion nozzle. The solution of the problem involves both the selection of the cooling method and the material to be used in constructing the throat section.

Reference 1 contains the results of an investigation performed at the Arnold Engineering Development Center (AEDC) using backside water cooling; Ref. 2 is a survey of copper base alloys for use in constructing nozzle throat sections. It is concluded from the stress analysis of Ref. 1 that for thin-walled, copper base alloy throats of 1/2-in. diameter operating at 100-atm stagnation pressure and utilizing nonboiling backside water cooling, the maximum heat flux that can be absorbed is about 5000 Btu/ft²-sec. Proposed full-scale propulsion testing facilities will require pressures greater than 100 atm and will have throat diameters on the order of 1 ft; consequently, the thicker walls required by these nozzles must operate at reduced heat fluxes.

Film cooling is one method that can be used to block some of the heat flux to a nozzle throat. Accordingly, an experiment was devised to measure the wall temperature distributions for a nozzle cooled only by an air film. Air was used as the film coolant because foreign vapors or gases were not wanted in the test section. Film cooling was used because some nozzle designs preclude any backside cooling in the location of the nozzle inlet because of the close proximity of a refractory air heater.

A supersonic nozzle with an 11/16-in. -diam throat and provisions for film cooling was constructed of stainless steel for the experimental investigation, and a 5-mw electric arc heater was used to supply heated air. This report presents the temperature distributions measured along the nozzle wall for various operating conditions and compares them with the distributions predicted by a theory developed by Roland (Ref. 3) of the University of Tennessee.

SECTION II DESCRIPTION OF TEST EQUIPMENT

2.1 GENERAL

The overall test configuration is shown in Fig. 1. The equipment consisted of a Linde N-4000 electric arc heater, a constrictor nozzle,

a stilling chamber, and the film-cooled nozzle instrumented with six surface thermocouples. Figure 2 is a photograph of the test installation.

2.2 STILLING CHAMBER

The stilling chamber was cylindrical in shape and had a stainless steel outer shell and a copper inner liner. Its internal diameter was 4 in., and its internal length was 6 in. The chamber was water cooled, and its cooling water channel was connected in series with the water channel in the constrictor nozzle at the exit of the arc heater. Openings in the chamber wall were provided for injection of cold air so that the temperature of the effluent from the arc heater could be reduced to a value measurable with platinum-platinum-rhodium thermocouples. Water-cooled rakes to measure pressure and temperature were positioned near the downstream end of the chamber.

2.3 FILM-COOLED NOZZLE

A drawing of the test nozzle giving dimensions and coordinates is shown in Figs. 3 and 4. The nozzle was made of Type 347 stainless steel and was instrumented with six Chromel-Alumel[®] thermocouples flush mounted to the surface to measure wall temperature. A drawing of a thermocouple is shown in Fig. 5. The flush surfaces of the thermocouples were machined in place to the contour of the nozzle wall. The junctions were formed by hand sanding across the face of the thermocouples after they were machined.

An injection plate made of René 41 metal was provided to introduce the film cooling air into the nozzle (see Fig. 4). A thermocouple was located upstream of the injection station so that the temperature of the entering film air could be measured.

SECTION III

TEST OPERATIONS

3.1 OPERATION OF TEST EQUIPMENT

Airflows into the arc heater, stilling chamber, and film injector were initiated, and the arc heater was energized for a period of 30 to 60 sec. Figure 6 shows nozzle wall temperatures as a function of time for a typical run. It is apparent that the temperatures approached but

did not attain equilibrium conditions. After the 30- to 60-sec run period, the arc heater was shut down, and the nozzle was allowed to cool to ambient temperature before the next run was made.

3.2 DATA RECORDING

Air temperatures and nozzle wall temperatures were recorded on tape by a data recording system that scanned each temperature once every 150 msec. All other parameters were recorded on a 36-channel oscillograph.

SECTION IV RESULTS AND DISCUSSION

4.1 STILLING CHAMBER

A pressure orifice was provided in the stilling chamber wall to obtain pressure measurements during each run. In order to determine the total pressure profile in the stilling chamber, a five-orifice total pressure rake was installed for Run K4. Total pressure profiles for this run are shown in Fig. 7. These profiles are nearly flat, and it is assumed that the total pressure profiles for the other five runs are also nearly flat.

The temperature profile in the stilling chamber was determined from the measurements of seven platinum-platinum-rhodium thermocouples mounted on a rake across the stilling chamber. The temperature rake was installed for Runs K2 and K3. Typical results from the temperature rake are shown in Fig. 8 for two stilling chamber test conditions. The temperatures were measured across the diameter of the chamber at a station approximately 2 in. upstream of the entrance to the film-cooled nozzle.

A comparison can be made between the average calculated temperature in the stilling chamber based on a heat balance and the rake data in Fig. 8a for total temperature and pressure of 2815°F and 574 psia, respectively, and in Fig. 8b for 3120°F and 516 psia. The temperatures indicated by thermocouples 2 and 7 were considerably lower than at the other five locations in Fig. 8a, and this observation was typical throughout the test program. A visual inspection of the rake revealed that thermocouples 2 and 7 were mounted so that the junctions formed were probably affected more by the nearby water-cooled components than the

other thermocouples. With less emphasis placed on thermocouples 2 and 7, the data indicate that a reasonably flat temperature profile existed in the stilling chamber.

Throughout the program, the average temperature level indicated by the rake thermocouples was about 400°F lower than the level calculated by a heat balance. The greatest difference recorded was 620°F, and this condition is shown in Fig. 8b. The temperatures indicated by the rake thermocouples are believed to be lower than the true temperature because of both radiation and conduction heat losses from the thermocouple junctions. The junctions were not radiation shielded from the water-cooled copper surfaces of the rake and stilling chamber. Also, the distance from the end of the water-cooled Inconel® sheath containing the thermocouple wires to the exposed junction was about 1/8 in., which provided a short heat conduction path through the lead wires. Therefore, the indicated rake temperatures were expected to be lower than the actual stream temperature. Consequently, the calculated total temperature was used to determine the theoretical wall temperature distributions shown in the next section.

4.2 NOZZLE WALL TEMPERATURES

The nozzle wall temperatures measured for various stilling chamber conditions and film air mass fractions are shown in Figs. 9a through h. Run durations were 30 and 60 sec, with Runs K1-1 and K2-1 being of 60-sec duration and all other runs of 30-sec duration. These run times were not of sufficient duration for the nozzle wall temperatures to reach an equilibrium value. Estimated equilibrium wall temperatures obtained by using one-dimensional, transient, adiabatic theory (Ref. 4) are shown in Fig. 9a for a 60-sec run and in Fig. 9c for a 30-sec run. It should be noted that the measured wall temperatures presented are not adiabatic wall temperatures, since there was some heat transferred externally through the outer surface of the nozzle during the tests. The heat transfer occurred because water vapor from cooling spray banks located downstream of the nozzle exit was recirculated onto the outer surface of the film-cooled nozzle. In actuality, then, the measured wall temperatures presented are near-equilibrium temperatures for a non-adiabatic condition. For each run, these measured temperatures are compared with the adiabatic wall temperatures as calculated from a theory developed and presented in Ref. 3. The calculated adiabatic wall temperatures show a continuous increase. On the other hand, the measured temperatures increase up to a point downstream of the throat and then begin to decrease. The decrease in the measured wall temperature is believed to be caused by external

convective heat transfer to the recirculated water vapor. This belief will be substantiated in the following discussion.

As shown in Fig. 9a, it is postulated that the wall temperatures measured by the first four thermocouples downstream of the injection station are correct and that the last two are low because of heat transfer to the water vapor. The first four points lie above the theoretical adiabatic curve by nearly a constant amount. If the curve of the measured temperatures is extended by this same ratio, an estimate of the wall temperature for the adiabatic condition can be obtained, as shown in Fig. 10. Using this estimated temperature distribution, calculating the inner wall convective heat-transfer coefficients by Bartz's method (Ref. 5) and assuming an external convective coefficient of $720 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$, the nozzle wall temperature distribution was calculated and is presented in Fig. 10. Wall temperatures were calculated by using a two-dimensional relaxation method. The results are believed to be valid because the calculated outer wall temperature at a point $1/2$ in. downstream from the nozzle flange agreed with temperature measurements made during the test run. The calculated and measured wall temperatures are very nearly the same, thus explaining the difference in the shape of the measured and the theoretical wall temperature curves shown in Figs. 9a through h.

Although the differences in the shape of the measured temperature distributions and the theoretical adiabatic wall temperature distributions may be explained by the external convective heat transfer, the difference in magnitude between the measured and theoretical distributions is not so easily accounted for. Some of the magnitude difference is probably caused by partial mixing between the mainstream and the coolant film, an effect that is not accounted for in the theory of Ref. 3. Another source of difference may be in the uncertainty of the value of transport properties used in Ref. 3 calculations. In any event, the theory of Ref. 3 underestimates the adiabatic wall temperatures by from 20 to 30 percent. With a different, and perhaps a better, geometry for introducing the film coolant so that mixing is minimized, better agreement between the measured and theoretical wall temperatures would probably be obtained.

SECTION V CONCLUDING REMARKS

An air film was used to cool the walls of a stainless steel nozzle. Reservoir stagnation conditions were pressures of about 500 psia and

temperatures ranging from 2616 to 3460°F. The nozzle surface extended 3.5 in. downstream of the injection station, and the nozzle throat diameter was 11/16 in. Cooling air film mass fractions ranged from 0.190 to 0.302, and the maximum nozzle wall temperature recorded was about 1800°F.

A comparison of measured wall temperatures with theoretical adiabatic values calculated from a theory developed and presented in Ref. 3 shows that the theory underestimates the wall temperatures by from 20 to 30 percent for this experiment. Introducing the air film so that mixing is minimized would probably result in better agreement with the Ref. 3 theory.

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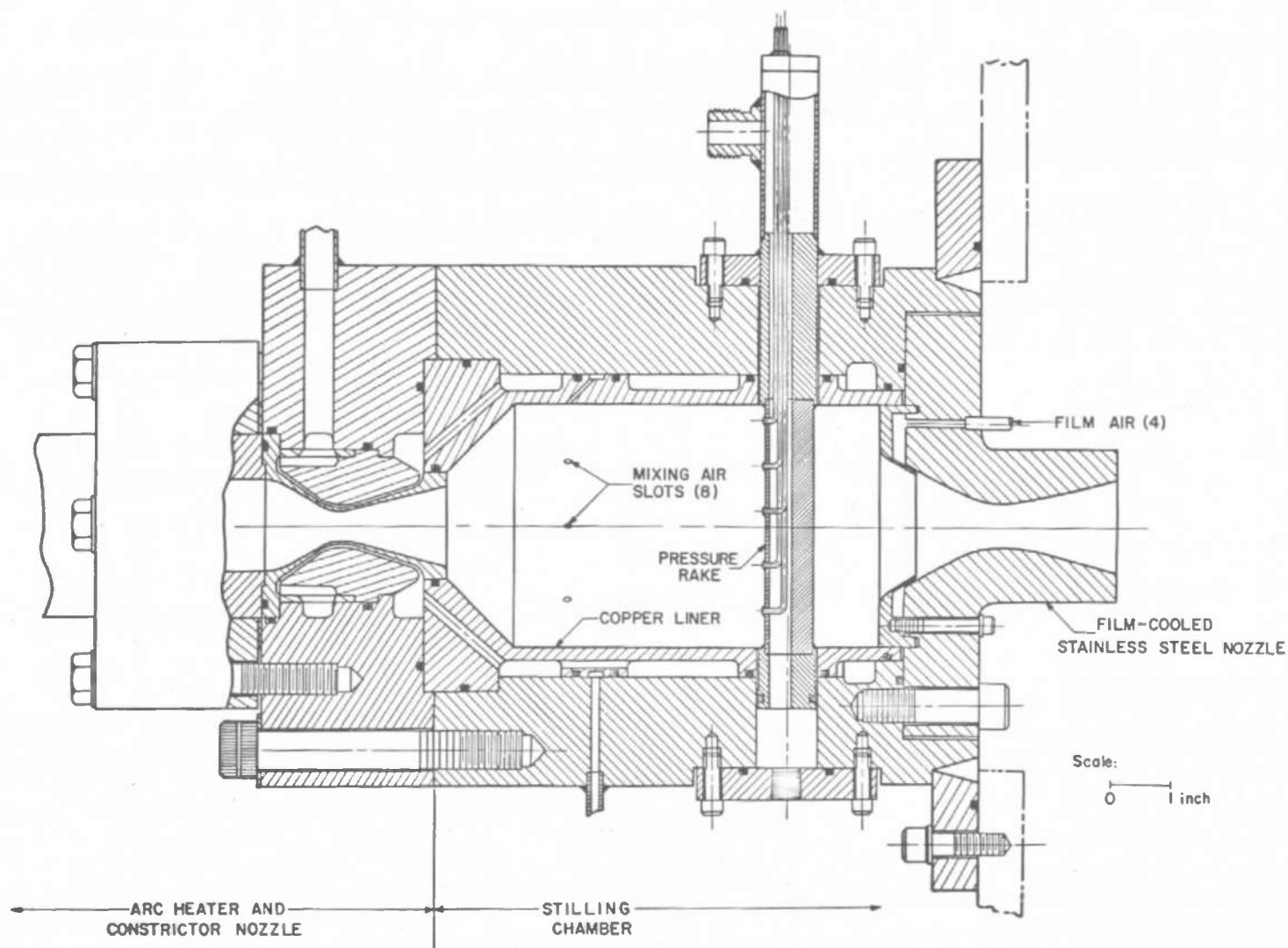


Fig. 1 Test Configuration

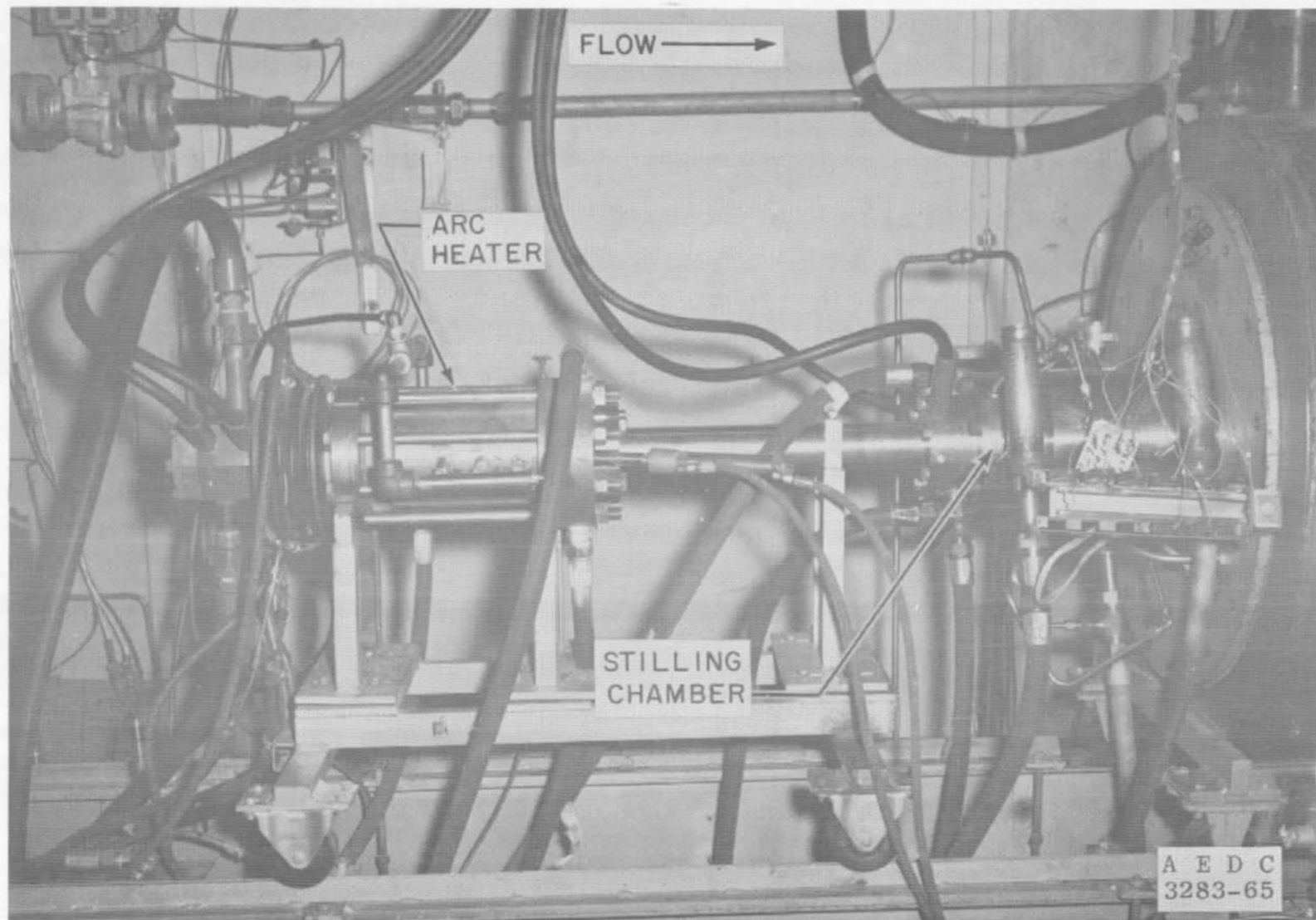
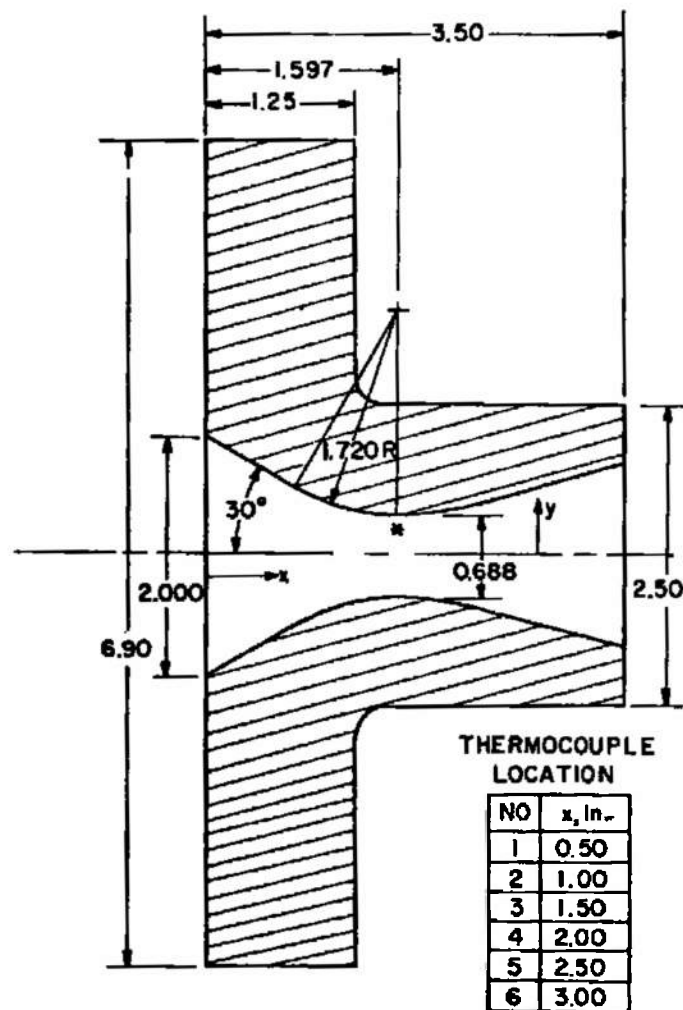


Fig. 2 Photograph of Test Installation

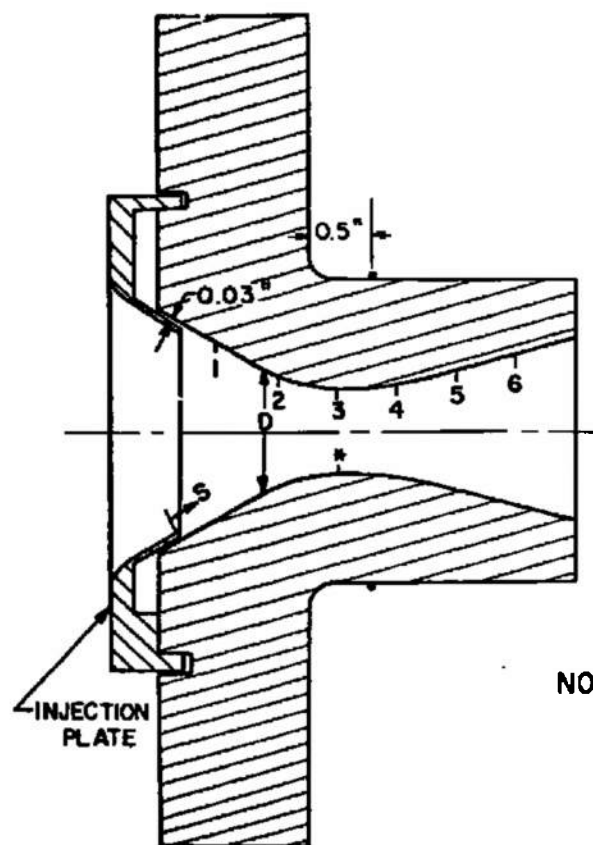


EXPANSION SECTION COORDINATES

x, in.	y, in.
1.597*	0.3440
1.700	0.3467
1.800	0.3552
1.900	0.3694
2.000	0.3879
2.100	0.4088
2.200	0.4312
2.300	0.4546
2.400	0.4787
2.500	0.5034
2.600	0.5286
2.700	0.5542
2.800	0.5801
2.900	0.6062
3.000	0.6325
3.100	0.6589
3.200	0.6854
3.300	0.7120
3.400	0.7387
3.500	0.7655

* Denotes geometric throat

Fig. 3 Nozzle Dimensions and Expansion Section Coordinates



NOTE:

S = Distance along nozzle surface measured from injection station

* Denotes geometric throat

• Surface thermocouples

NOZZLE COORDINATES

S, inches	D, inches	S, inches	D, inches
0	1.769	1.70	0.706
0.10	1.669	1.80	0.731
0.20	1.569	1.90	0.766
0.30	1.469	2.00	0.806
0.40	1.369	2.10	0.849
0.50	1.269	2.20	0.896
0.60	1.169	2.30	0.940
0.70	1.075	2.40	0.988
0.80	0.985	2.50	1.036
0.90	0.911	2.60	1.085
1.00	0.843	2.70	1.135
1.10	0.791	2.80	1.186
1.20	0.747	2.90	1.237
1.30	0.715	3.00	1.288
1.40	0.695	3.10	1.339
1.50	0.689	3.20	1.391
1.521 (*)	0.688	3.30	1.442
1.60	0.692	3.40	1.493
		3.473	1.531

THERMOCOUPLE LOCATION

NUMBER	S, inches
1	0.346
2	0.912
3	1.421
4	1.927
5	2.439
6	2.956

Fig. 4 Nozzle Coordinates Used to Calculate Theoretical Wall Temperature Distributions

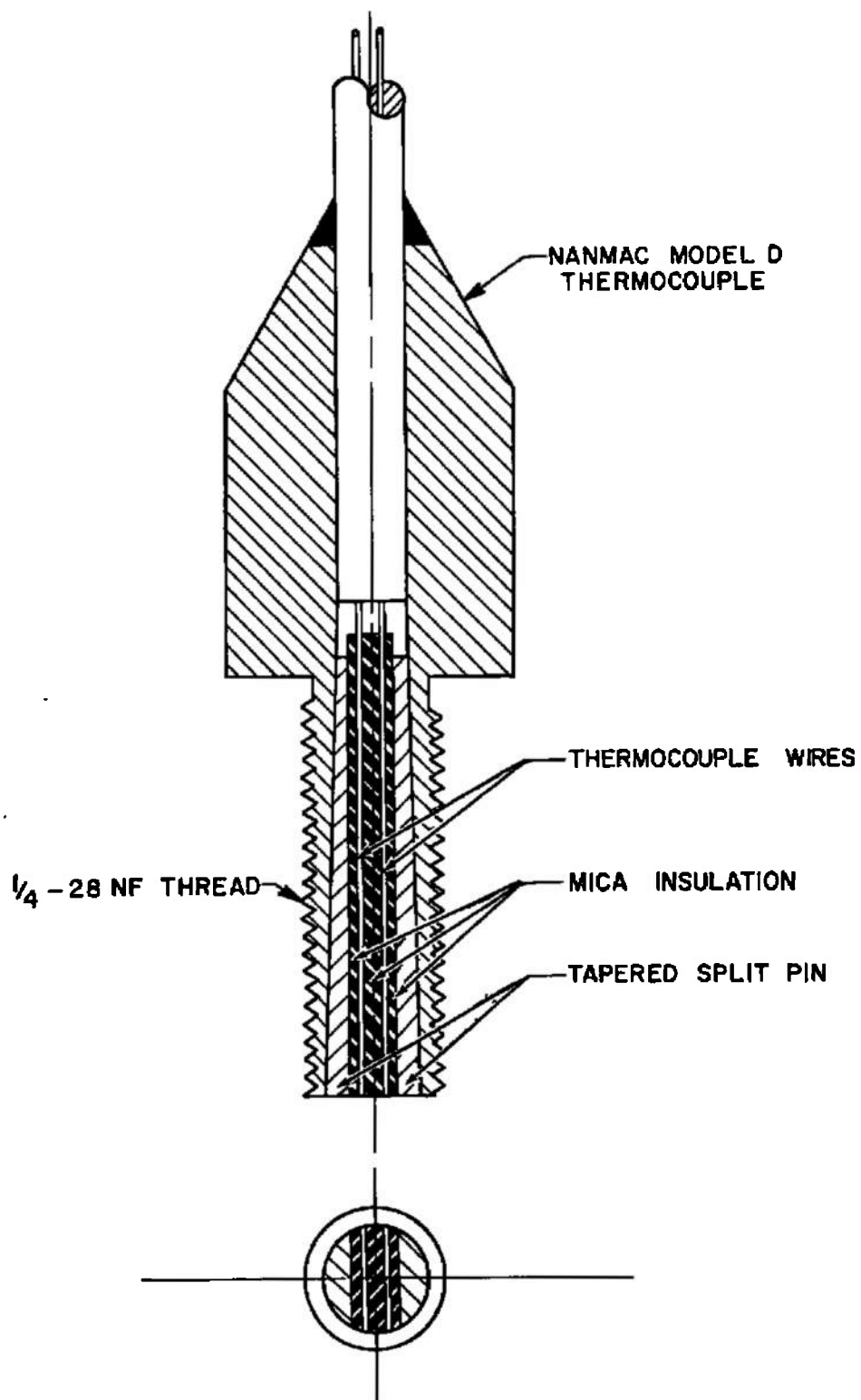


Fig. 5 Chromel-Alumel Thermocouple Used to Measure Nozzle Wall Temperature

RUN K2-1
 $p_0 = 574$ psia
 $T_0 = 2815$ °F
 $\theta = 0.296$

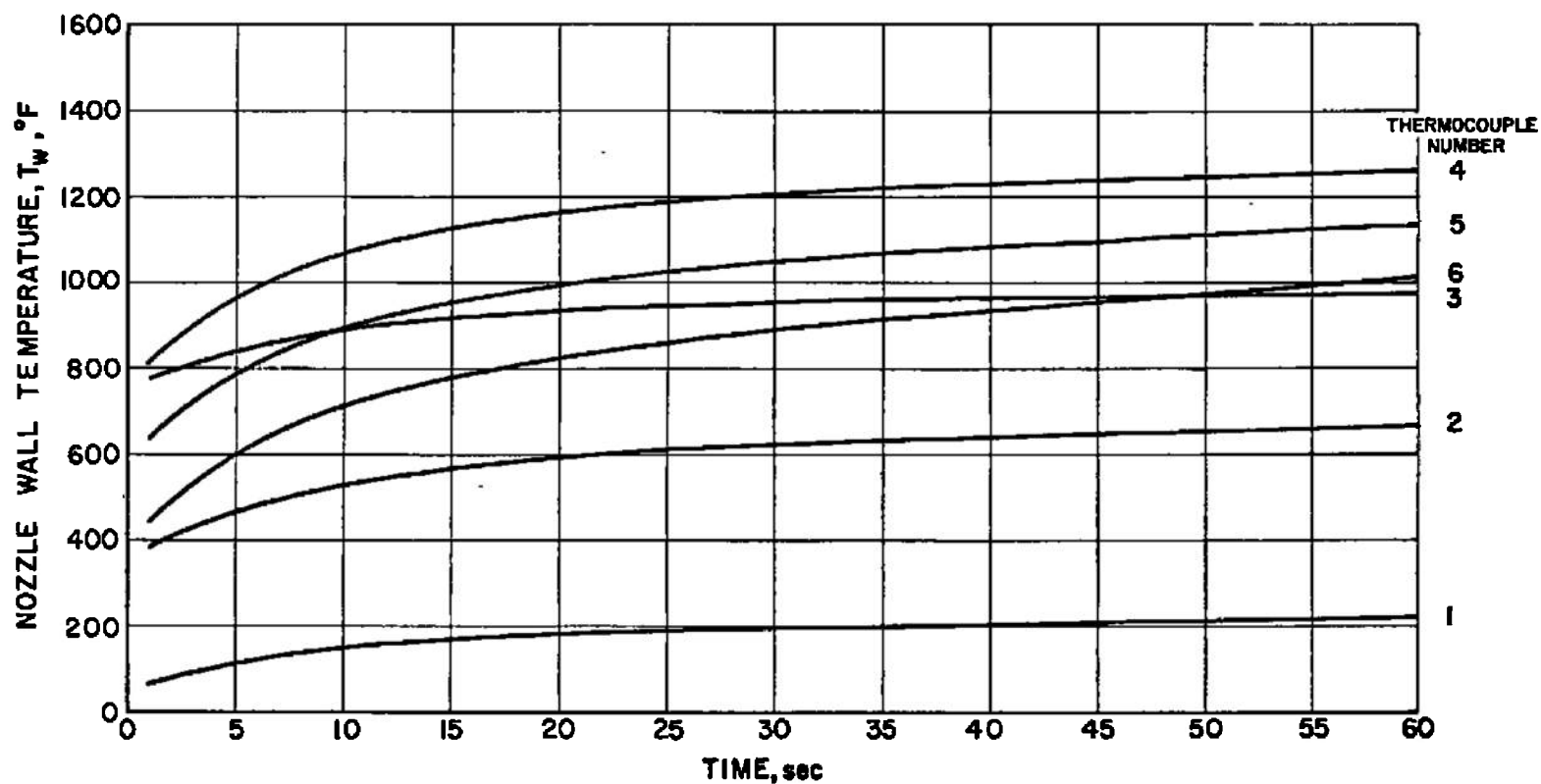


Fig. 6 Nozzle Wall Temperature versus Time for a Typical Run

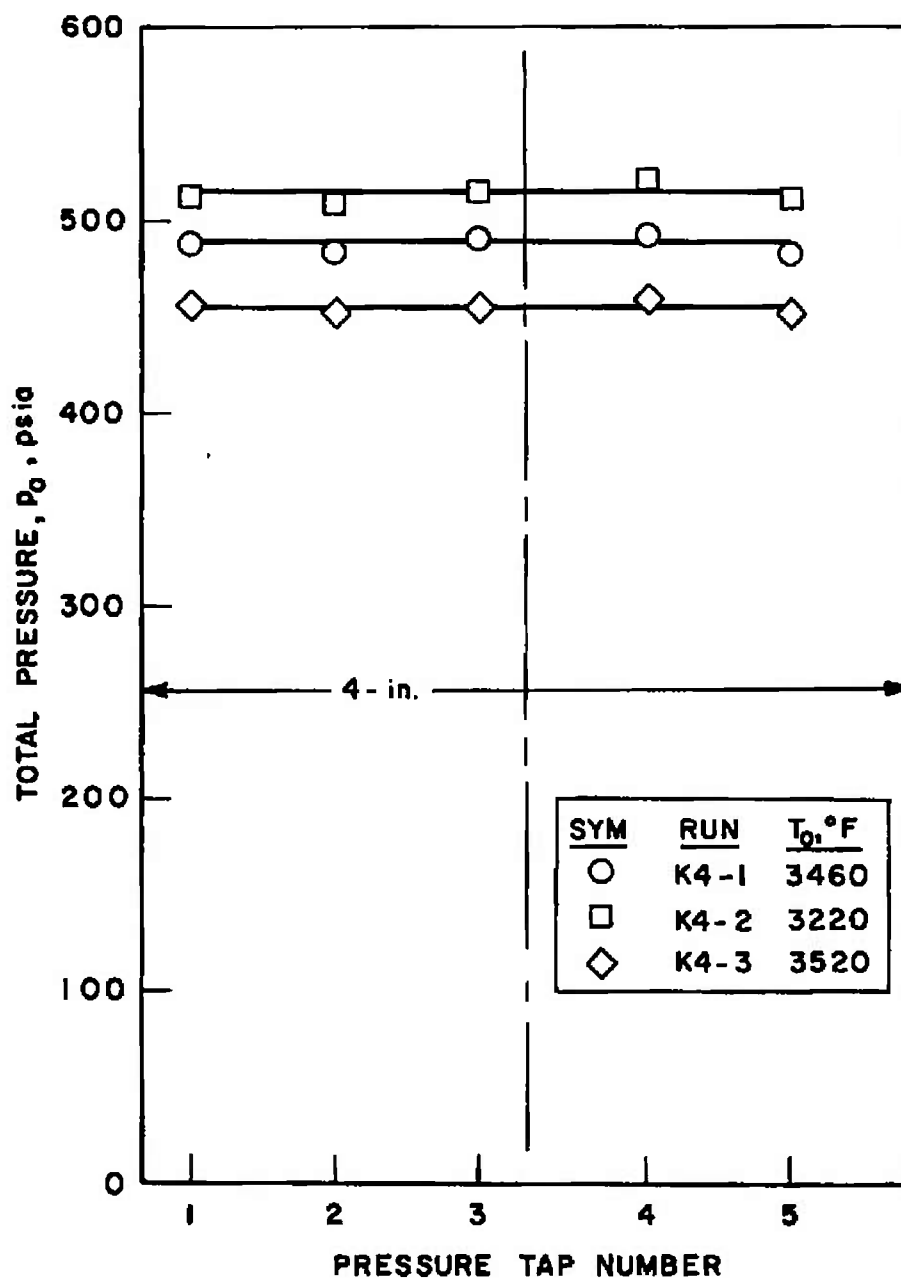
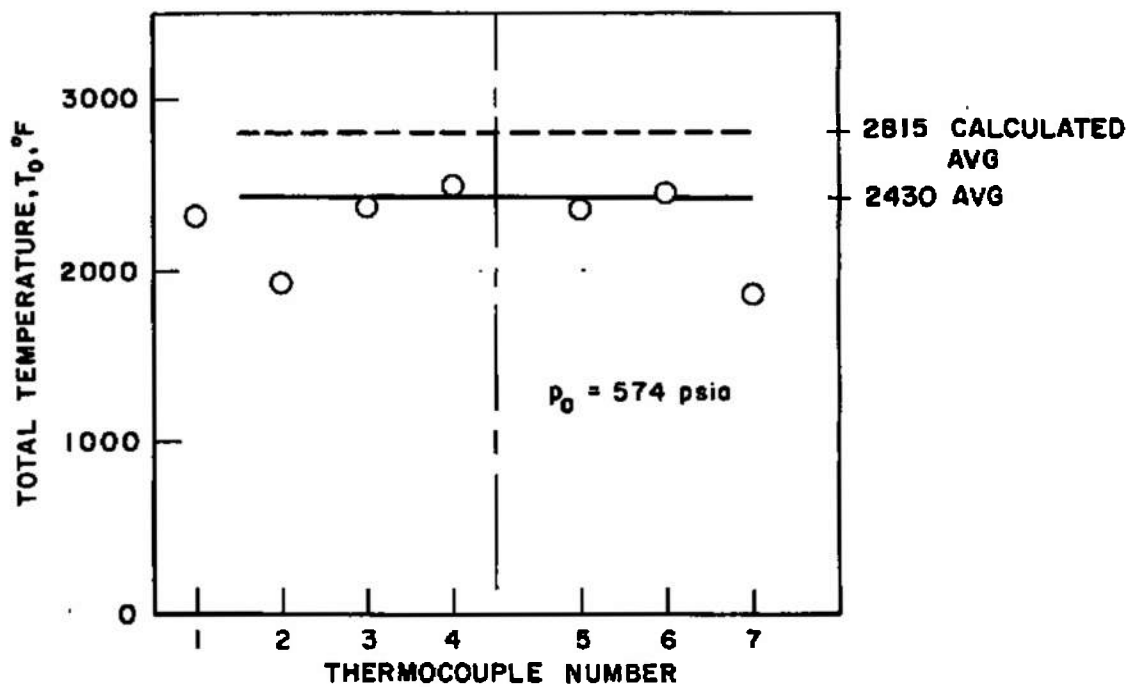
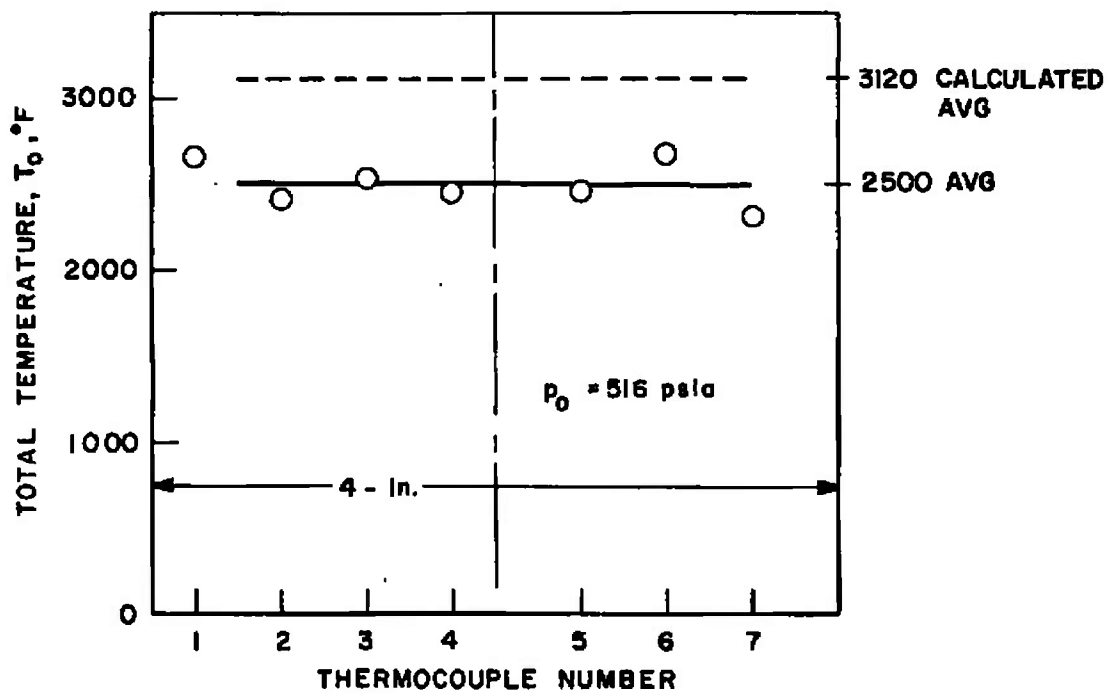


Fig. 7 Total Pressure Distributions in the Stilling Chamber

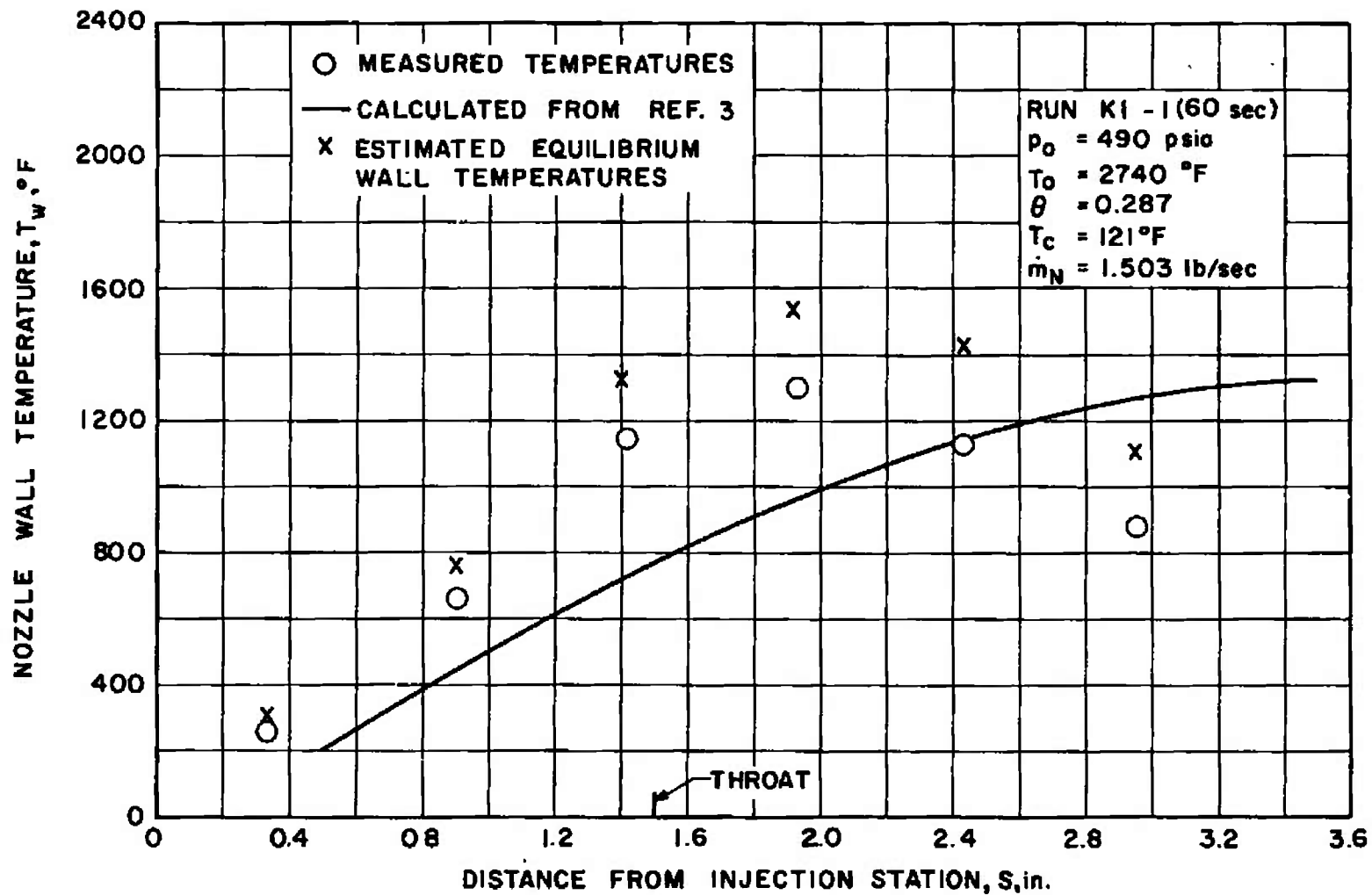


a. Run K2-1



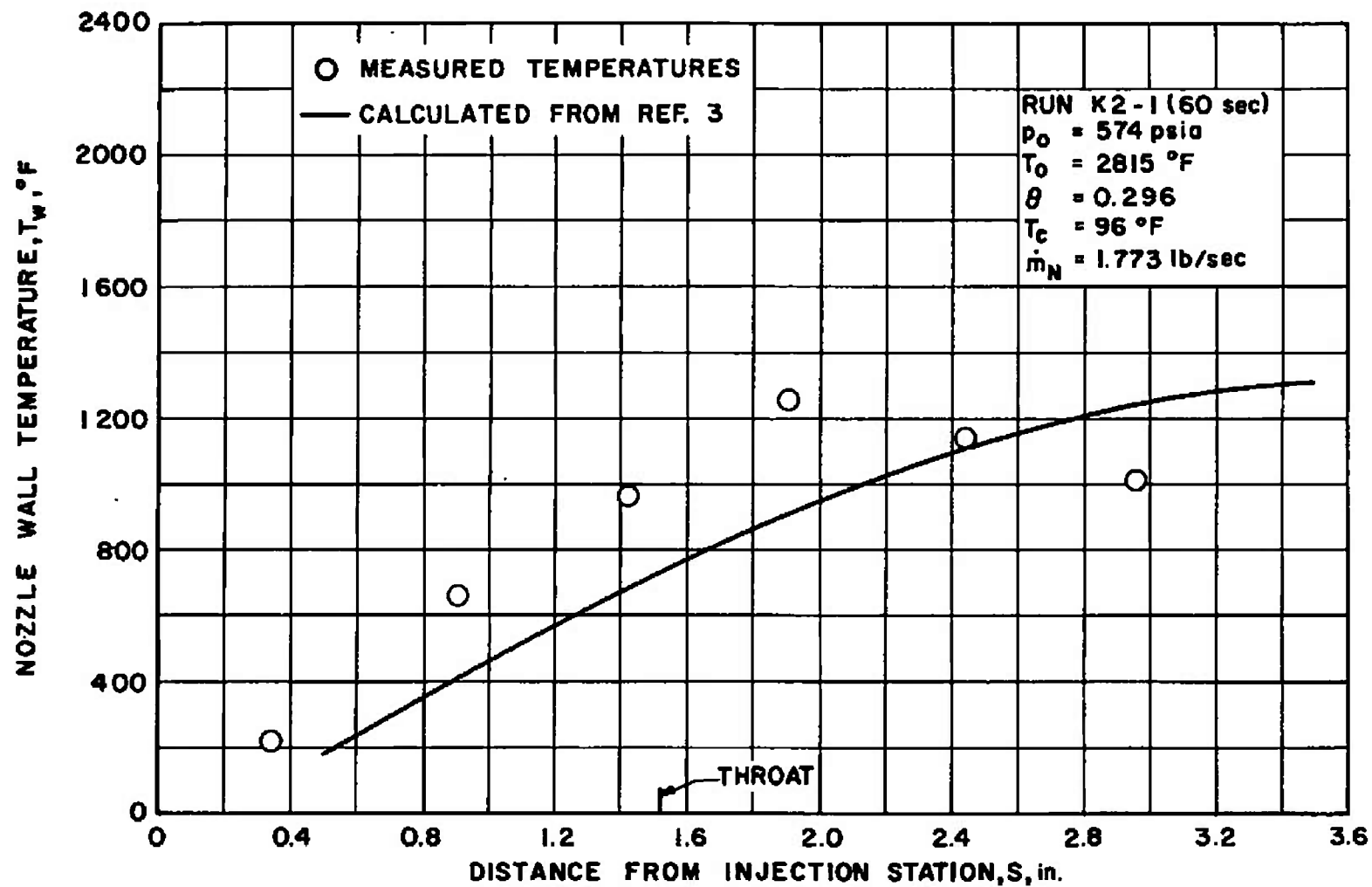
b. Run K3-3

Fig. 8 Total Temperature Distributions In the Stilling Chamber



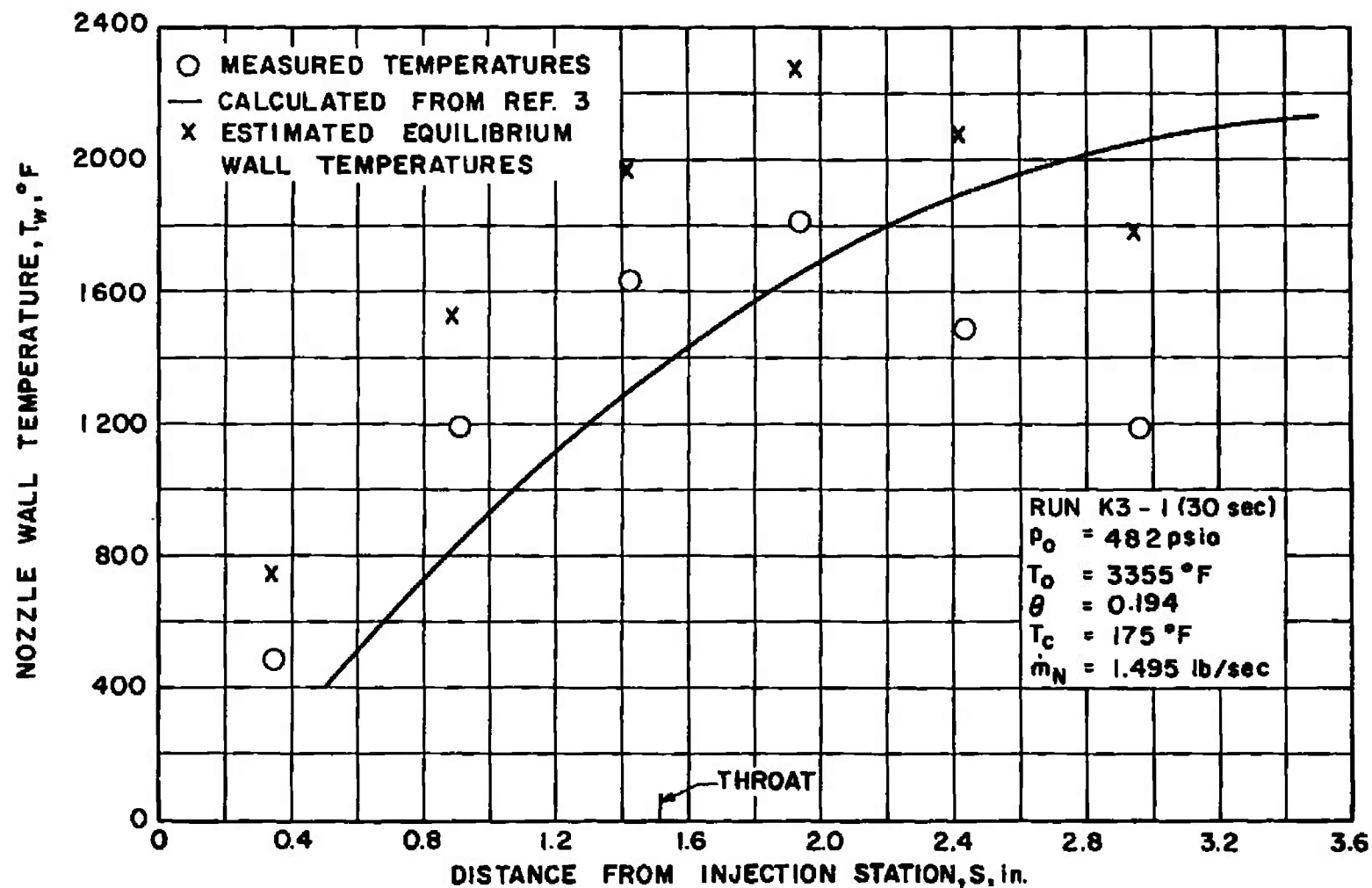
a. Run K1-1

Fig. 9 Comparison of Measured and Theoretical Nozzle Wall Temperatures



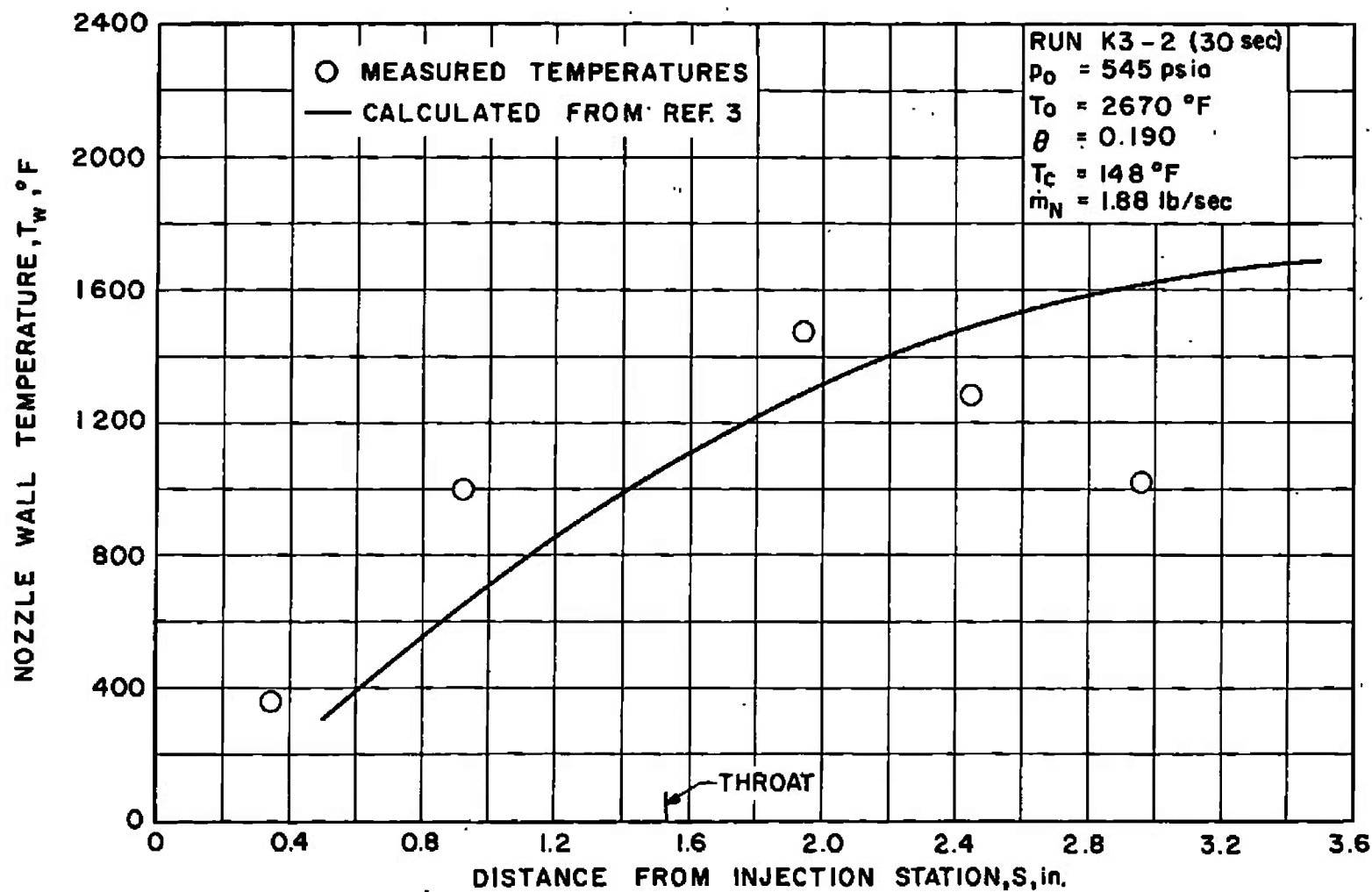
b. Run K2-1

Fig. 9 Continued

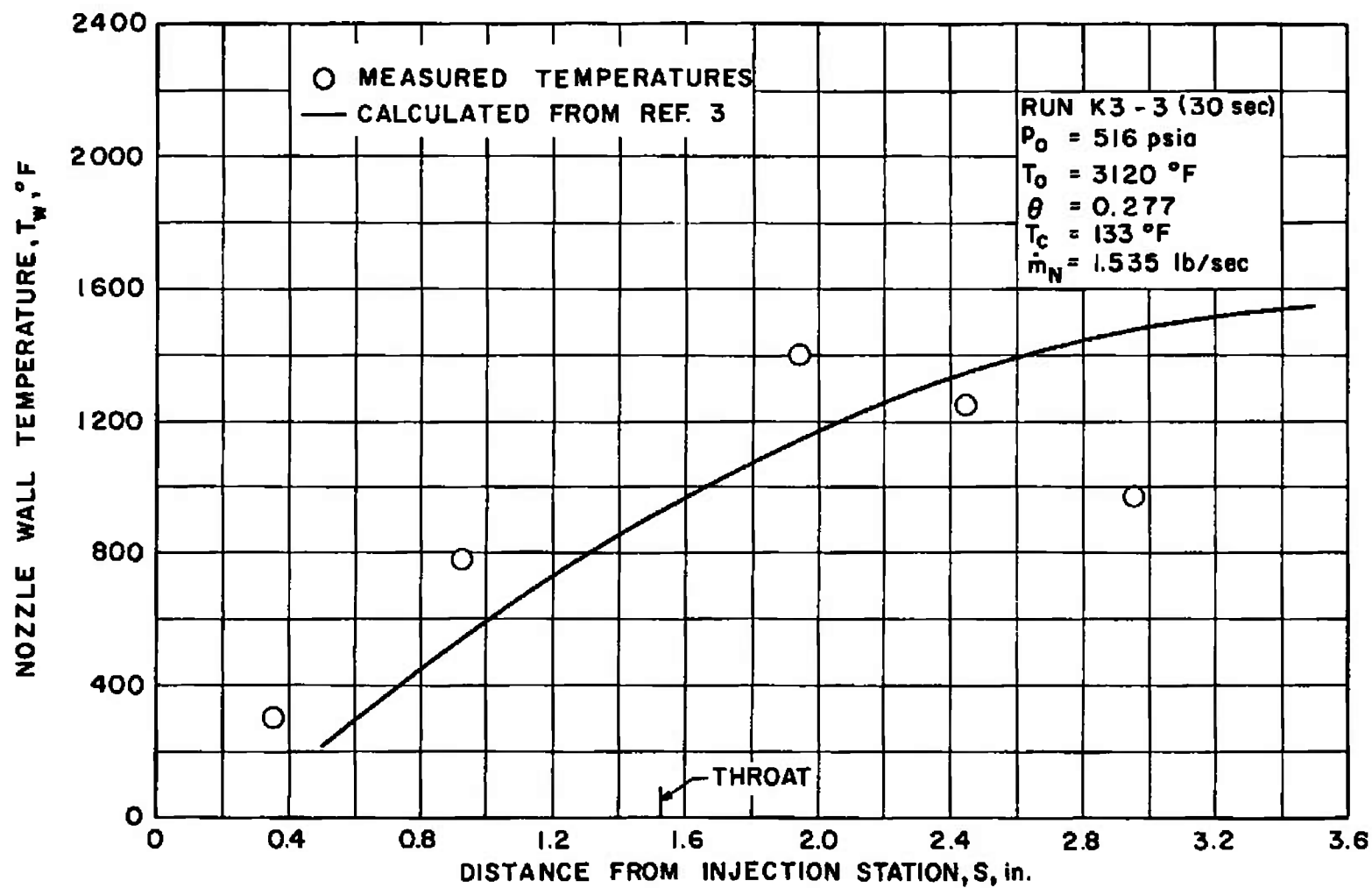


c. Run K3-1

Fig. 9 Continued

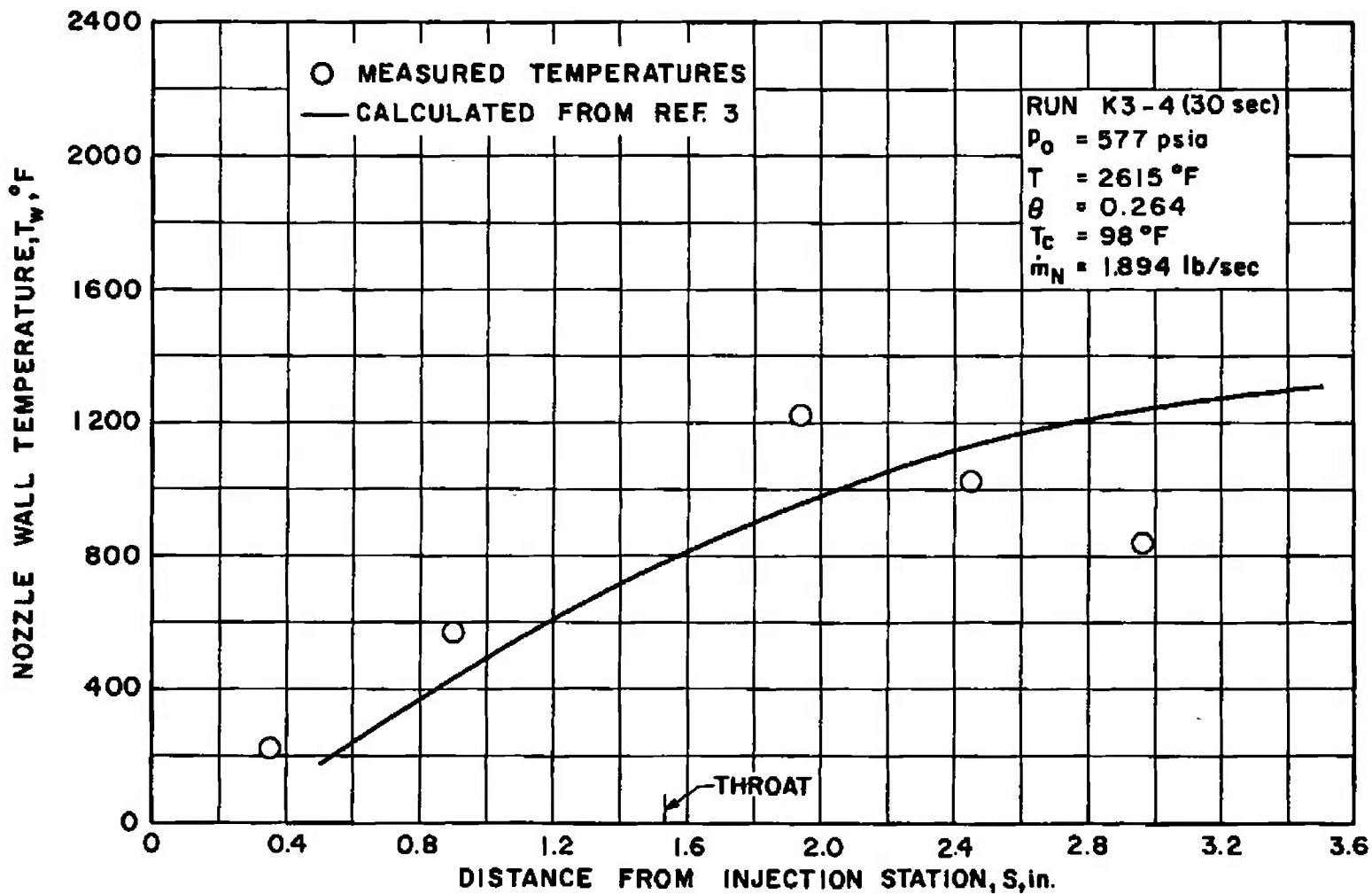


d. Run K3-2
Fig. 9 Continued



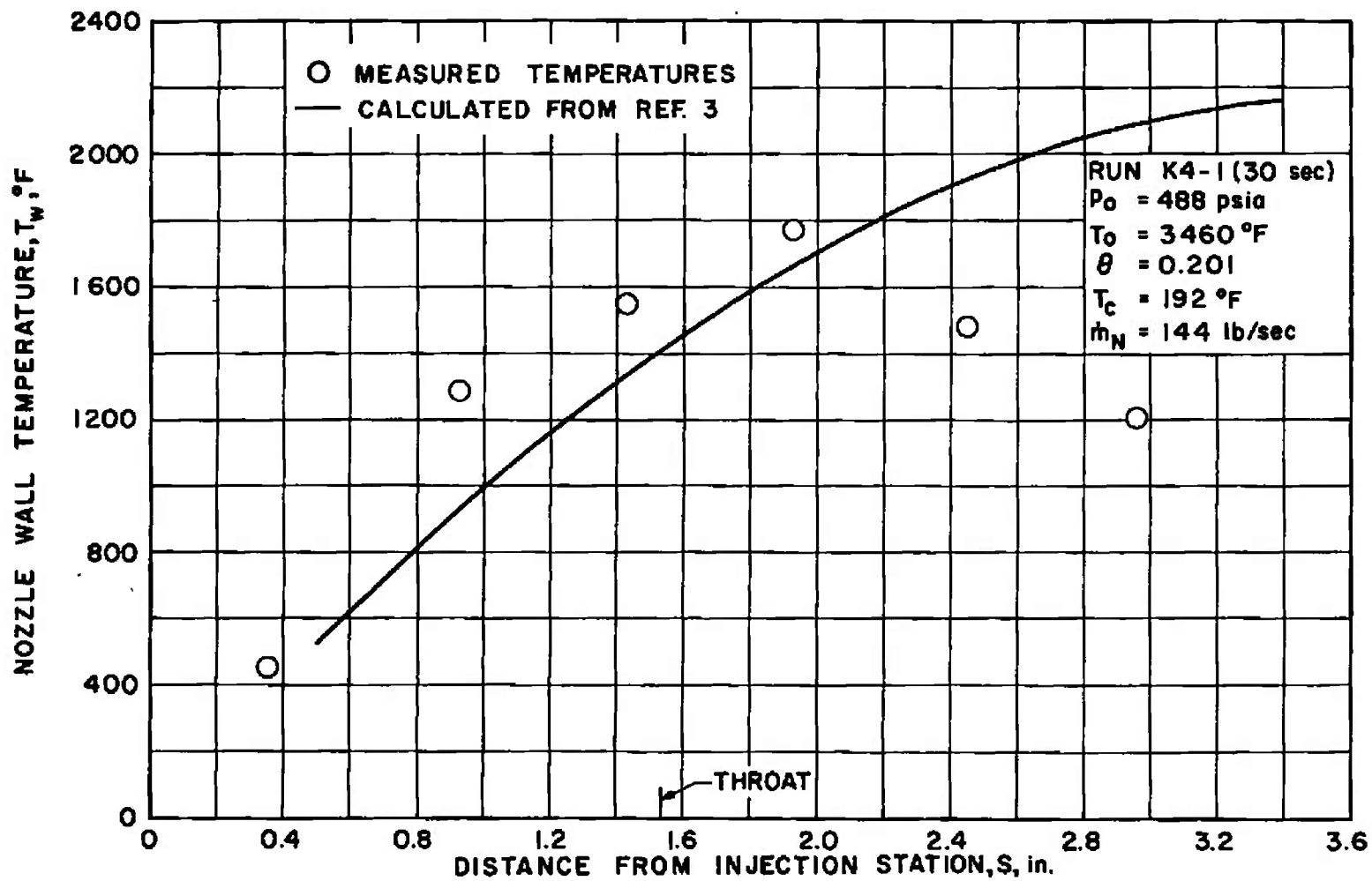
e. Run K3-3

Fig. 9 Continued



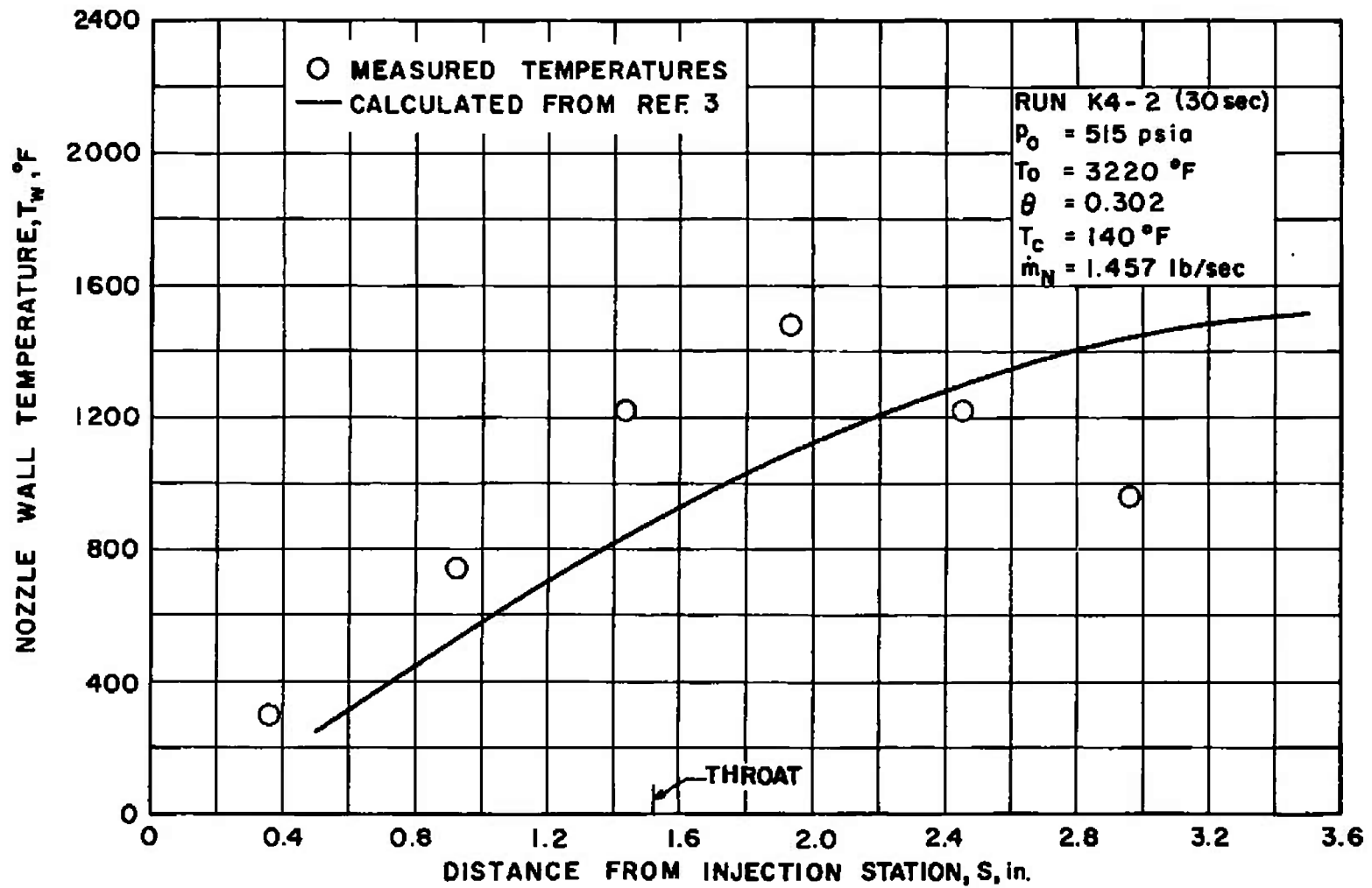
f. Run K3-4

Fig. 9 Continued



g. Run K4-1

Fig. 9 Continued



h. Run K4-2

Fig. 9 Concluded

RUN KI-1

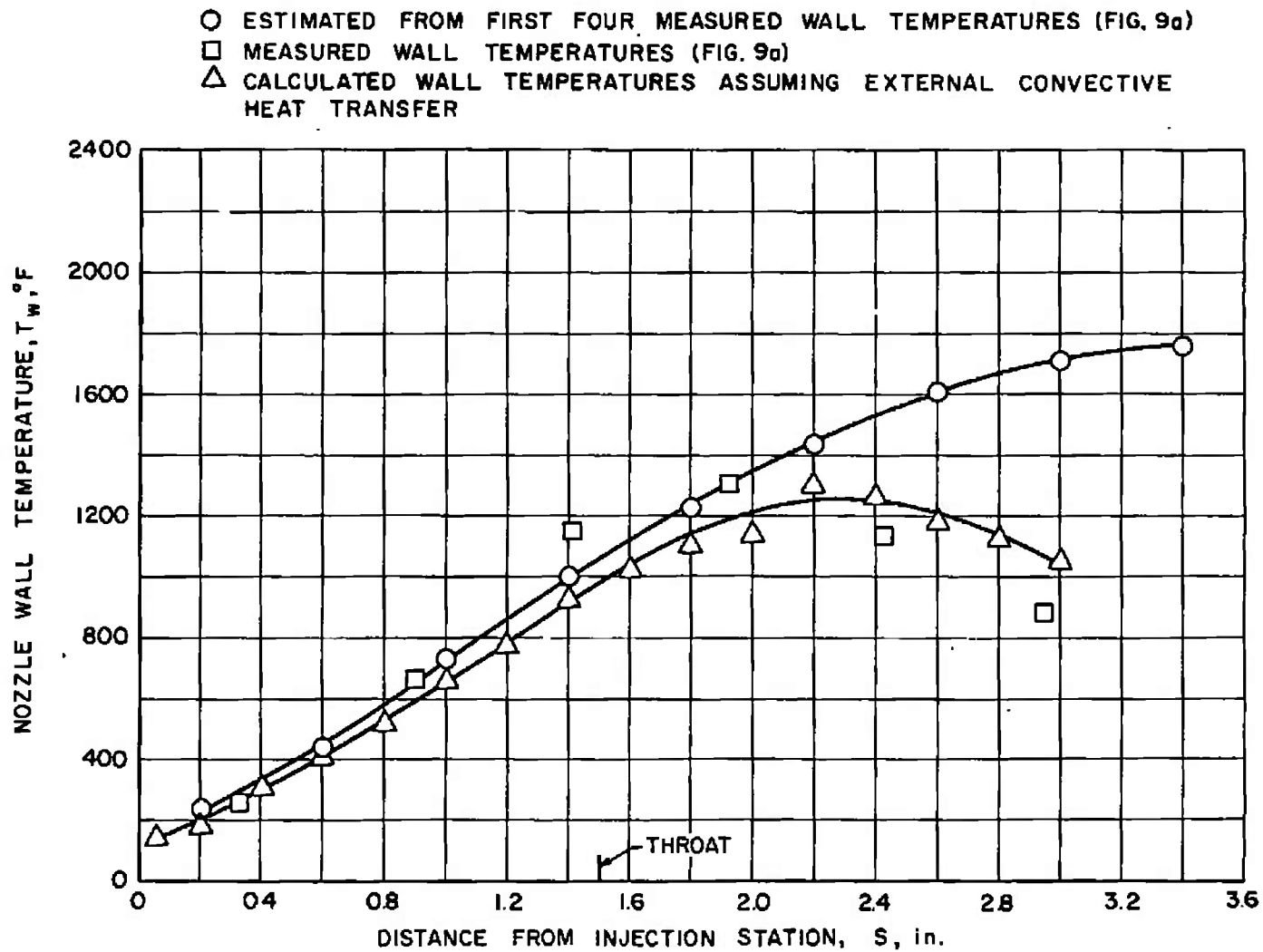


Fig. 10 Comparison between Estimated, Measured, and Calculated Wall Temperatures

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KEY WORDS

1 supersonic nozzles - 8
cooling
wall temperatures

1-98

2. ~~supersonic~~ nozzles - 5
pressure distribution

3 wind tunnel nozzles
temperature distributions

4. Nozzles - cooling

5 " " - pressure distribution

6 Film cooling

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It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as (TS), (S), (C), or (U).

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. **KEY WORDS:** Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical content. The assignment of links, rules, and weights is optional.